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ISOON-BASED INVESTIGATION OF SOLAR ERUPTIONS

Edward W. Cliver

30 October 2013

Final Report

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AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

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Dr. Edward W. Cliver	Edward J. Masterson, Colonel, USAF
Program Manager, AFRL/RVBXS	Chief, Battlespace Environment Division

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14. ABSTRACT

We examined ISOON (Improved Solar Optical Observing Network) telescope observations, in conjunction with other ground- and spaced-base data sets, of eruptive solar events in order to improve understanding of the origins of severe space weather. Principal results included: (1) the identification of the recently-discovered changes in line-of-sight photospheric magnetic fields during flares as an impulsive phase phenomenon linked to the main acceleration phase of coronal mass ejections (CMEs); and (2) the first unambiguous demonstration that solar Moreton waves are driven by the lateral expansion of CMEs. This second result underscores the value of ISOON data, used in combination with high-cadence coronal images from spacecraft such as the Solar Dynamics Observatory and the Solar Terrestrial Relations Observatory (STEREO), for probing the dynamics of energetic eruptions on the Sun.

15. SUBJECT TERMS

Sun – Flares; Sun – Coronal Mass Ejections; Sun – Moreton Waves; Flares – Impulsive Phase; Flares - Implosions

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1. Introduction

Space weather is a growing concern for modern society because of our increasing reliance on electrical and electronic infrastructure. In recent years, the threat posed by extreme space weather has been documented in a series of high level reviews by the US National Research Council (NRC; 2008), the JASON Defense Advisory Panel (2011), and the Royal Academy of Engineering (2013). The NRC report estimated that the cost to the US of a superstorm comparable to the 1859 event (Cliver and Svalgaard, 2004; Cliver 2006) would be $1-2 trillion. Such an event would give rise to a defense as well as an economic national emergency because of its impact on a broad range of Department of Defense surveillance and communications systems.

The three-year basic research effort, funded by the Air Force Office of Scientific Research (AFOSR), that is summarized in this Final Report was aimed at using ISOON (Improved Solar Optical Observing Network) data (Neidig et al., 1998), in conjunction with other ground- and spaced-base data sets, to improve understanding of the origins of severe space weather, with the ultimate goal of accurately predicting major solar events, i.e., eruptive flares, and mitigating their impact. The proposed work had had two principal foci: (1) the timing relationship between abrupt magnetic field changes during flares and acceleration of coronal mass ejections (CMEs); and (2) signatures of eruptive solar events. For the first of these topics, we determined that the magnetic field changes occur during the flare impulsive phase, the identified main acceleration phase of CMEs in eruptive flares. This research was published in the Astrophysical Journal (Cliver et al., 2012; Scientific Report No. 1). For the second topic, we showed for the first time that a solar Moreton wave was driven by the lateral expansion of a CME (published as an AFRL Preprint Tech Report (White et al., 2013; Scientific Report No. 2). A related paper (Cliver, 2013; Scientific Report No. 3), a solicited review for Nature Physics, summarizes recent progress in the understanding of the large-scale solar waves which characteristically accompany energetic CMEs.

2. Summary of Results

2.1 Abrupt Changes of the Photospheric Magnetic Field in Active Regions and the Impulsive Phase of Solar Flares

It has long been suspected that the free energy in solar flares resides in active region magnetic fields (e.g., Smith & Smith, 1963). It is only in the last decade, however, that convincing evidence has accumulated for magnetic field changes in flares. Specifically, several authors have reported flare-associated changes in the line-of-sight or longitudinal component of flare associated magnetic fields (e.g., Kosovichev & Zharkova, 2001; Wang et al., 2002; Sudol & Harvey, 2005).

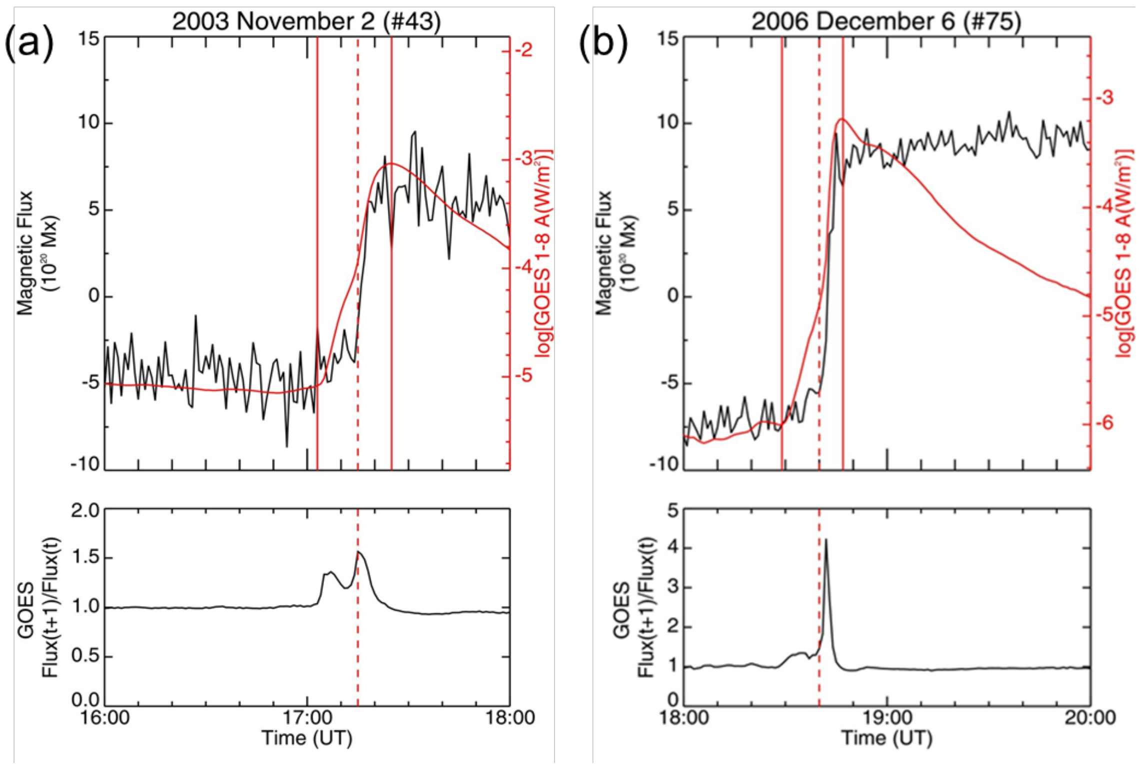

Figure 1. Time profiles of the spatially integrated unsigned magnetic fluxes and the 1–8 Å intensities of the soft X-ray (SXR) flares (top) and the logarithmic derivatives of the flare SXR intensities (bottom) on (a) 2 November 2003 and (b) 6 December 2006.

In Figure 1, the solid red vertical lines mark the start and peak times of the SXR burst and the dashed red line indicates the onset of the flare impulsive phase.

Early timing comparisons of the time profiles of the magnetic field changes and soft X-ray (SXR; 1-8 Å) flares showed that the field changes lagged the onset of flares and thus could not be causing them but rather were a consequence of flares. However, these studies did not consider the timing of the flare impulsive phase, the time of most rapid energy release (Hudson, 2011) which characteristically lags the flare onset by ~3 minutes (Veronig et al., 2002).

In our study we compared the unsigned magnetic flux time profiles [observed by the Global Oscillation Network Group (GONG; Harvey et al., 1988)] with their associated SXR light curves for 75 large (≥M5) SXR flares, noting the timing of the magnetic changes relative to the onset of the SXR flare impulsive phase, as well as the flare start and peak time. An illustration of this analysis for two large events in our sample is shown in Figure 1. In both cases, the onset of the flare impulsive phase (dashed red line) agrees well with the sharp onset of the step in the unsigned magnetic flux and the peak of the SXR flare corresponds to the end of magnetic flux increase.

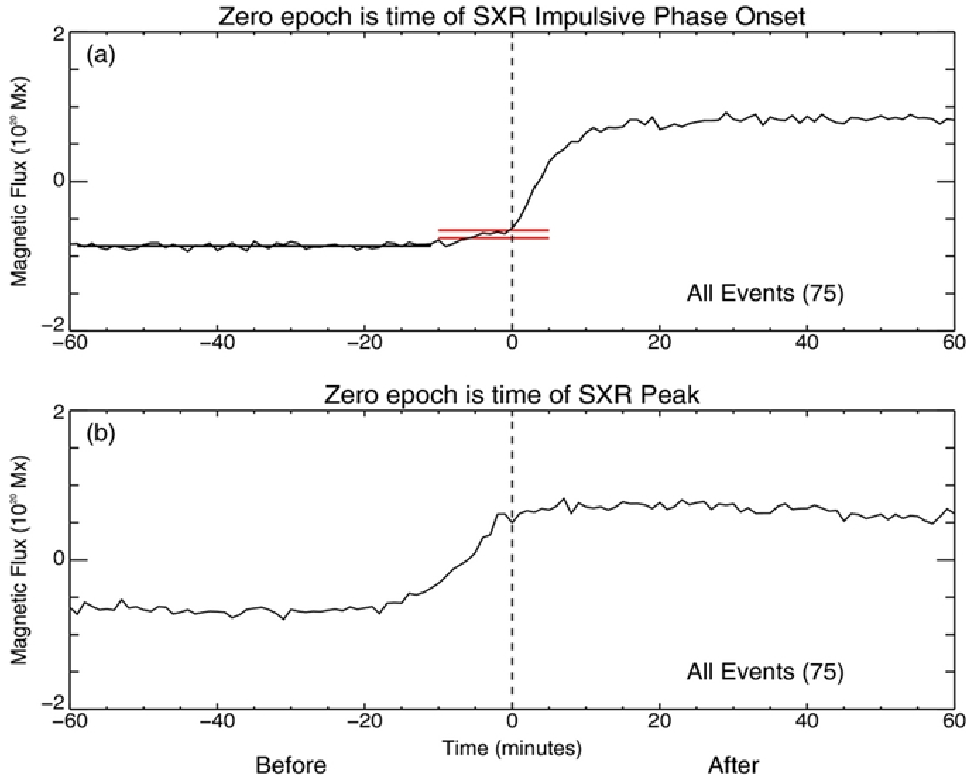

Figure 2 Superposed epoch plots of the unsigned magnetic flux variation in a flaring region measured by GONG magnetographs for 75 ≥M5 events.

In Figure 2, the zero epoch corresponds to the onset of the flare impulsive phase in SXRs in (a) and to the peak of the SXR emission in (b). In (a), the black horizontal line is the mean of the trace for the interval from 60 minutes to 10 minutes before the time of zero epoch and the red lines are drawn 3σ and 6σ above the mean from –10 minutes to +5 minutes relative to zero epoch.

To see if this result applied generally, we made a superposed epoch analysis of the magnetic flux changes for all 75 events in the sample, using as the zero epoch both the onset and the peak of the flare impulsive phase. The corresponding plots are shown in the top and bottom panels of Figure 2 where it can be seen that, on average, the impression given in Figure 1 is confirmed. The magnetic step or principal abrupt flux change corresponds to the time bracketed by the two SXR time markers. To make certain that this result was not completely due to the largest events in the sample, we repeated this analysis for the third of the sample with the smallest (well-defined) steps, obtaining essentially the same result.

The above analysis reveals that the magnetic flux steps observed in the longitudinal component of the photospheric magnetic field are a phenomenon of the flare impulsive phase. This span of time from the sharp rise of the SXR flux to the flare maximum corresponds to epoch when the energy stored in coronal magnetic fields is rapidly converted to particle acceleration and plasma heating (Neupert, 1968) and, pertinent to this effort, the main phase of CME acceleration in eruptive flares

(Zhang et al., 2001). The fact that the inferred coronal field changes are simultaneously observed in the photosphere (in contradiction of standard flare theories; Sudol and Harvey, 2005) implies that, at minimum, the field changes are rapidly transmitted downward from the corona, perhaps via Alfvén waves (Fletcher and Hudson (2008). Another, more speculative possibility is that the field changes represent magnetic implosions or collapsing loops (Hudson, 2000). This would make the field more horizontal, reducing the line-of-sight component.

2.2 16 July 2004: A Large Confined Flare

As an off-shoot of the above work, we investigated a large well-documented confined (i.e., CME-less or non-eruptive flare) on 16 July 2004 with the assistance of Dr. Alexei Pevtsov of the NSO staff. The flare, beginning at 13:49 UT, had an X3.6 SXR maximum and was an Hα class 3B flare observed by ISOON (Figure 3). Only one other comparably large confined flare, an X4.0 (optical class 4B) flare on 9 March 1989 (Feynman and Hundhausen, 1994), has been reported. While March 1989 flare was

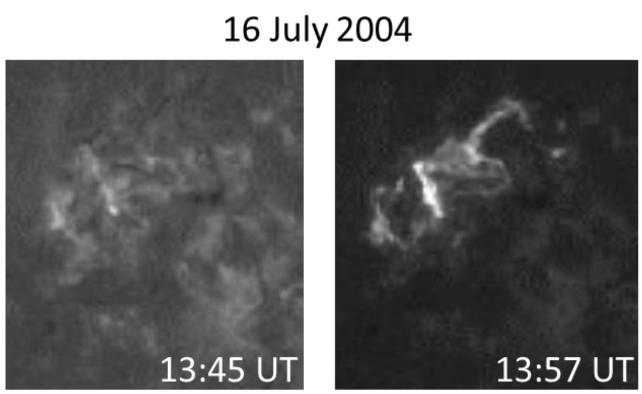

Figure 3 ISOON pre-flare (13:45 UT) and maximum (13:57 UT) images of the confined class 3B flare on 16 July 2004.

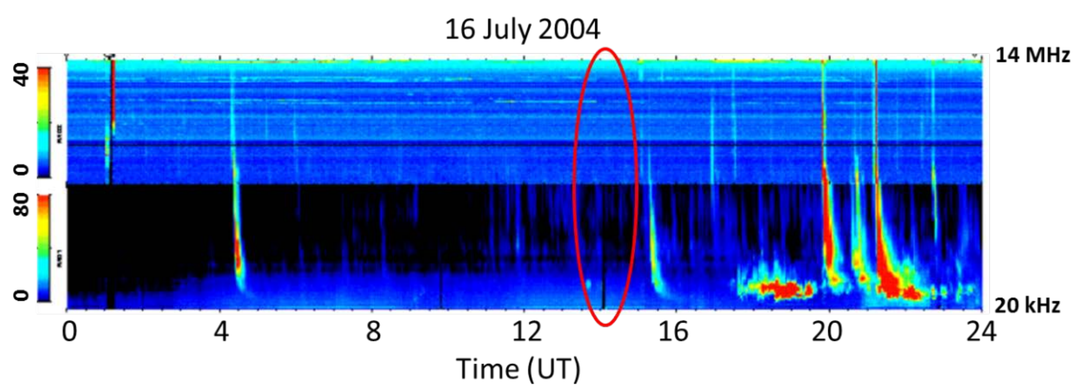

Figure 4 Wind Waves low frequency radio observations showing the absence of radio emission during the time of the X3.6 flare.

In Figure 4, if the X3.6 flare had been an eruptive event, one would have expected to see type III bursts such as those recorded near 4, 20, and 21 UT.

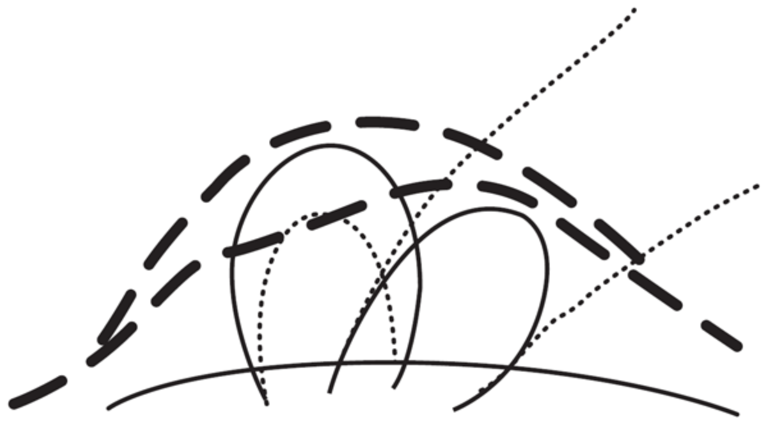

Figure 5 Schematic representation of a magnetic implosion.

In Figure 5, magnetic reconnection of the two pre-event (solid line) loops results in a magnetic implosion indicated by formation of a smaller (dotted line) loop and reduction of the magnetic energy of the active region (lowering of the dashed contour lines). Loop retraction has been hypothesized by Hudson (2000) to be the source of free energy for flares. [Adapted from Hudson and Cliver, 2001.]

larger, the observations of the July 2004 event provide more compelling evidence for confinement, in particular, the absence of low-frequency (14 MHz – 20 kHz) radio emission by the Wind Spacecraft WAVES radio experiment (Bougeret et al., 1995) in the red oval in Figure 4 encompassing the time of the flare.

Because this large flare lacked a CME, we reasoned that it would be a particularly good example to look for evidence of implosion – a "naked implosion", not complicated by the cataclysmic rearrangement of fields that mark an eruptive flare. We examined Transition Region and Coronal Explorer (TRACE; Handy et al., 1999) images at 171 Å for such an event. A cartoon of what we hoped/expected to see is shown in Figure 5. Where the two solid line loops crossed, we expected to see brightening and then retraction of one or both loops toward the surface either prior to or during the impulsive rise phase of the flare. What we saw (Figure 6) was something close to this but not enough so that we found it to be compelling evidence for an implosion. In Figure 6, the two red arrows in the 171 Å image at 13:40:08 UT point to two loops (A and B) that are suggestive of the two solid line loops in Figure 4 while the brightening where the two loops intersect, indicated by the arrow in the following frame, suggests magnetic reconnection. So far, so good. What we failed to see, however, was definitive evidence of accompanying loop retraction. Rather, loop A appeared to dim in place. Shortly before the flare we see brightening, clearly apparent at 13:48:13 UT, of a loop C underlying A, but this loop expands in time. Recently, definitive evidence of loop contraction during the impulsive phase of eruptive flares (e.g., Gosain, 2012, Simões et al., 2013) has been provided by observations of the Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) on the Solar Dynamics Observatory (SDO). To the best of our knowledge, however, no implosion has yet been observed for a confined flare.

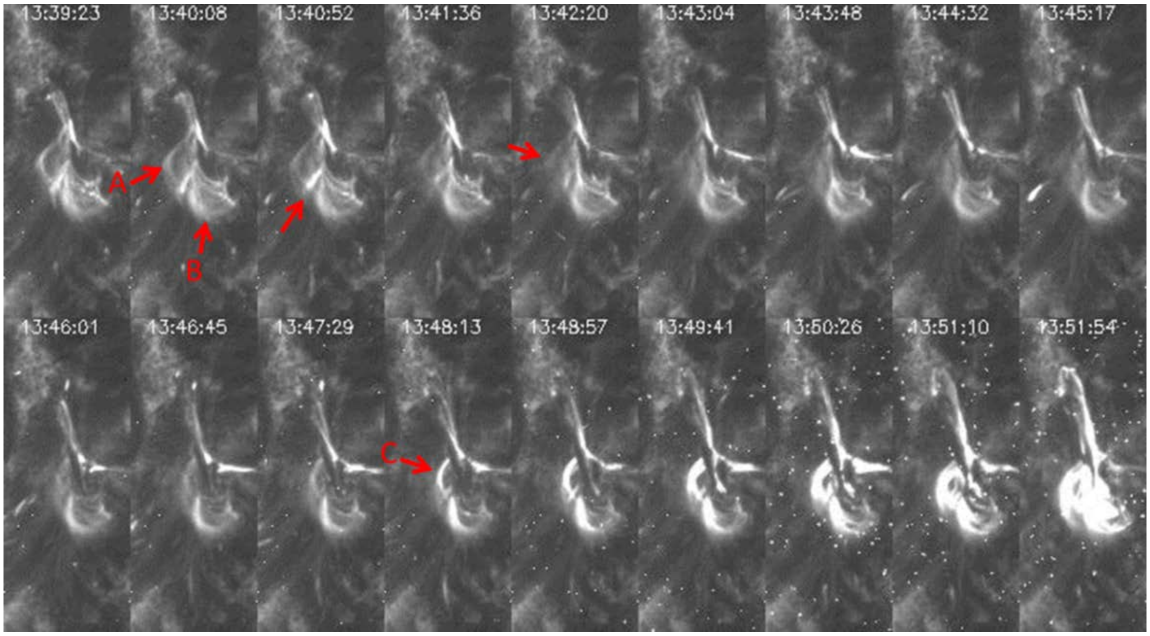

Figure 6 Candidate implosion event associated with a large confined flare on 16 July 2006 in a sequence of 18 Trace 171 Å images from 13:39:23 – 13:51:54 UT.

2.3 Direct Comparison of a Solar Moreton Wave, EUV Wave, and a CME

One of the more widely-debated questions in recent solar physics has been the origin of large-scale waves, designated as radio type II bursts (Cliver et al., 1999; Vršnak and Cliver, 2008), Moreton waves, or EUV-waves, depending on their wavelength of observation. The two leading candidates for Moreton wave drivers are CMEs and a flare pressure pulse. During the last several years, the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) suite of imagers (Howard et al., 2008) on the Solar Terrestrial Relations Observatory (STEREO) spacecraft and the AIA on SDO have greatly advanced our understanding of large-scale waves, as will be summarized in section 2.3. Because of their relative rarity, however, the origin of Moreton waves has not been conclusively demonstrated. A Moreton wave on 9 August 2011 (Asai et al., 2012) has been attributed to a CME as was a very-well observed (by ISOON) Moreton wave on 6 December 2006 (Balasubramaniam et al., 2010). In both cases, however, definitive coronagraph observations were not available.

Fortunately, the eruptive flare associated with a Moreton wave recorded by ISOON on 14 February 2011 was well-observed by imagers/coronagraphs on both STEREO and SDO. EUV (211 Å) and Hα (6563 Å) images of the large-scale wave are shown in the right and left panels, respectively, of Figure 7. Time distance plots for the propagation of the wave in various wavelengths are shown in Figure 8 where it can be seen that the EUV and Hα waves have essentially the same trajectory and speed. Closer inspection reveals that the Hα response lags slightly behind the EUV disturbance and also that the Hα Doppler response lags behind the centerline emission. The fact that the Moreton wave is delayed slightly behind the EUV wave and the further delay of the Doppler signal relative to the Hα center-line emission is consistent with the

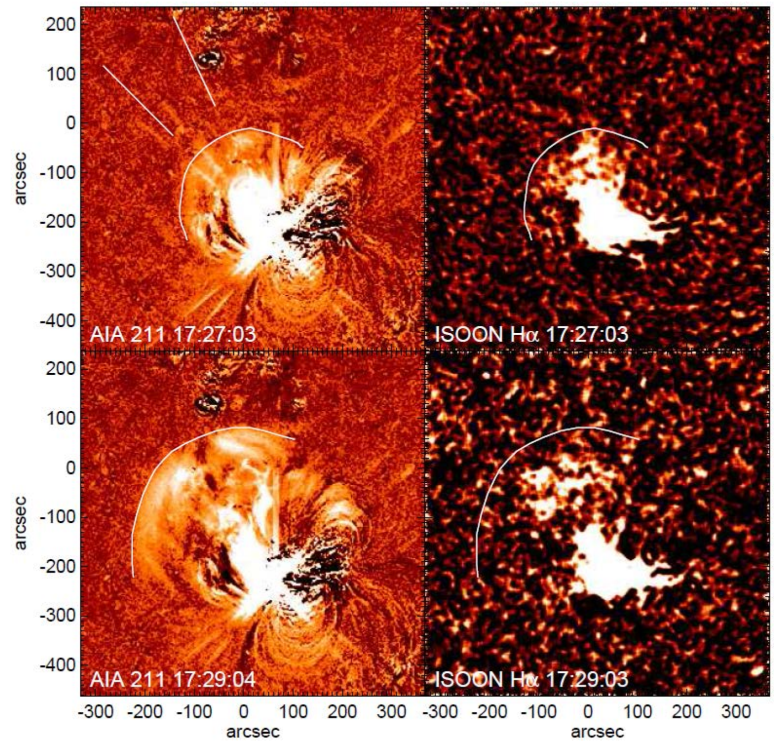

Figure 7 EUV (left) and Hα (right) images of the wave from the 2011 February 14 flare.

In Figure 7, the images are shown roughly 4 (upper panels) and 6 minutes (lower panels) after the onset of the impulsive phase of the flare, and are differenced against a pre-flare image. White arcs are drawn on each of the panels at the location of the leading edge of the wave in the AIA 211 Å images at the time of the image.

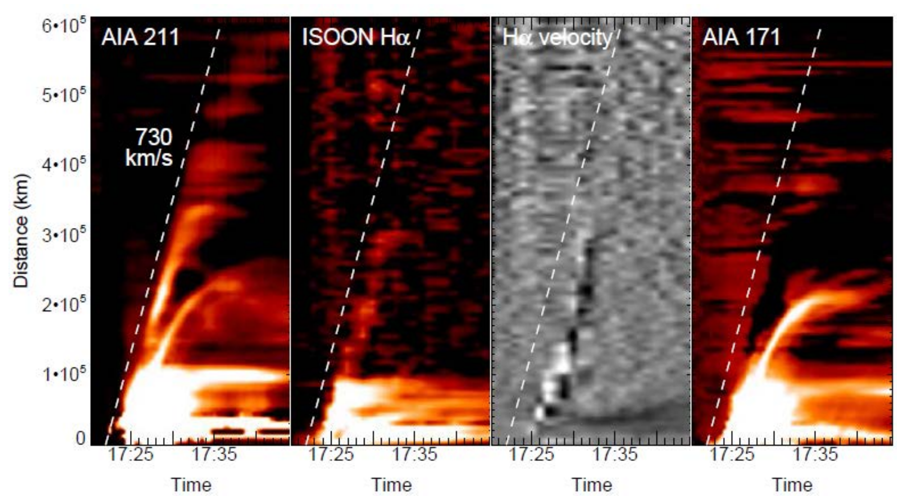

Figure 8 Time–distance plots for the wave in 211 Å images (1st panel), Ha line center images (2^{nd}), Doppler images (3rd, with red–shifted emission bright and blue–shifted emission dark), and 171 °A images (4th).

In Figure 8, the dashed line in each panel corresponds to a disturbance travelling from the flare site at 730 km s^{-1}.

picture in which a pressure increase in the corona acts to compress the chromosphere from above, enhancing the density and driving the top of the chromosphere downwards.

In the AIA panels in Figure 8, we see two propagating features, one travelling slower than the other and decelerating. One interpretation of such a double structure is that the fast disturbance is a fast-mode MHD wave and the slower disturbance is associated with the CME. However, STEREO coronagraph and EUV imaging data suggest that the faster wave in this event is coincident with the leading edge of the mass ejection. Inspection of the SDO AIA images suggest that the slower structure, which becomes stationary before it reaches the active region at the top of the AIA images (and therefore is not a reflection), consists of slower moving material that leaves the flare site later than the fast disturbance and becomes becalmed in the region between parent active region and the region to the north. The identification of the Moreton wave with the lateral expansion of the CME provides the most direct evidence to date that Hα chromospheric waves, like the large-scale waves observed at other wavelengths, are driven by coronal mass ejections.

2.4 Making Waves: Recent Progress in Understanding Large-Scale Solar Waves

As noted above, the imagers and coronagraphs on the STEREO and SDO missions have led to rapid progress in our understanding of large-scale waves on the Sun, including the Moreton waves observed by ISOON. To put this rapid increase in knowledge in perspective, I was asked by Nature Physics to write a News and Views article in conjunction with a paper by Carley et al. (2013) that touched on many of the recent developments in this field. The following paragraphs are taken from the resulting Cliver (2013) paper which was entitled “Making Waves”.

The study of large-scale waves on the Sun began in the late 1940s with the discovery of metric type II radio bursts that are characterized by a drift to lower frequencies at a rate of ~0.5 MHz s^{-1} (Payne-Scott et al., 1947). The causative disturbance, later identified as a magnetohydrodynamic shock wave, propagated outward through the corona with a speed of 500–750 km s^{-1}. The optical counterparts of type II bursts — observed in 6563 Å emission from hydrogen — propagate along the solar surface with comparable speeds (Moreton and Ramsey, 1960). A key development was the proposal that the compression of the chromosphere that is responsible for the optical wave was due to the ‘sweeping skirt’ of a coronal type II shock wave (Uchida, 1974). In 1998 research on large-scale solar waves was given fresh impetus when the EUV telescope on SOHO detected coronal waves (Thompson et al., 1998). Large-scale waves were subsequently reported in soft X-rays, 10830 Å emission from helium atoms, and microwaves. A close kinematical relationship between the various manifestations of large-scale waves implied a common origin (Warmuth et al., 2004).

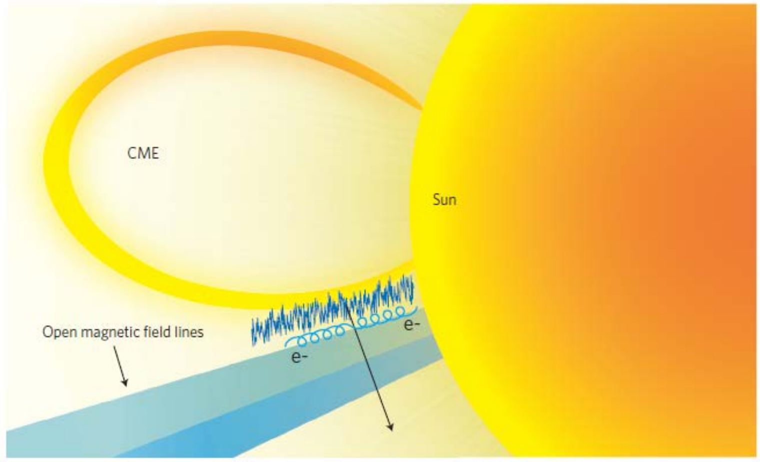

Figure 9 Schematic showing the relationship between a laterally expanding CME, a coronal bright front, and a quasi-perpendicular shock for the eruptive event of 22 September 2011 analyzed by Carley, et al. (2013). [From Cliver, 2013].

In the past several years, solar scientists have used the new high-cadence imagery from the STEREO spacecraft (launched in 2006) and SDO (from 2010) to establish a strong link between CMEs and large-scale waves (Veronig et al., 2008). In short, CMEs drive these waves. Progress in this area includes recognition of the importance of the lateral (rather than radial) expansion of CMEs for surface wave creation (Kienreich et al., 2009), culminating in the unambiguous identification of a quasi-perpendicular type II shock wave at the Sun by Carley et al. (2013; Fig. 9). In addition, a clear distinction is forming between moving EUV phenomena (called pseudo waves) associated with the CME itself as a result of field line stretching or magnetic restructuring (Chen et al., 2005), and true waves that are initially driven by the CME and later become freely propagating when the lateral expansion of the CME stops (Liu et al., 2012, Patsourakos and Vourlidas, 2012).

3. Conclusion

In this effort, we used ISOON data, in conjunction with space-based data to probe the origins and dynamics of eruptive (and one confined) flare. We regard the principal results of this effort as the following: (1) the identification of the recently-discovered changes in line-of-sight photospheric magnetic fields during flares as an impulsive phase phenomenon linked to the main acceleration phase of CMEs; and (2) the first unambiguous demonstration that solar Moreton waves are driven by the lateral expansion of CMEs.

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